Simulating the Effect of Strategies to Increase Transit Ridership by Reallocating Bus Service

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ABSTRACT

Despite significant investment, transit ridership across most American cities has been declining even prior to COVID-19. In this paper, we evaluate three strategies that transit operators might consider to increase ridership: consolidating service on bus routes serving the highest share of low-income riders, consolidating service on those bus routes with the highest ridership, and consolidating high-ridership bus routes in combination with giving those routes exclusive bus lanes. In each scenario, we double the service frequency of buses on the focus routes and reduce the frequency on all other routes to maintain the exact total vehicle revenue miles. In this way, we expect all three scenarios to be roughly operating-cost neutral. We tested these scenarios for Oshkosh, Wisconsin, and Atlanta, Georgia, using a modeling framework that combines CityCast, a commercially available data-driven planning tool to replicate observed travel patterns, and MATSim to simulate how travelers would change the route, mode, and time-of-day of the trips they make in response to the service changes. The results show substantial ridership gains for all but one scenario, suggesting that these strategies may provide a promising, low-cost means of increasing transit ridership.

KEYWORDS: Transit, Simulation, Ridership, CityCast, MATSIM

INTRODUCTION

Despite significant investment, transit ridership across most American cities has been declining since 2014 [1]. The declining trend is worrisome because traditional factors that influence transit ridership are insufficient to explain the entire decline [2]. A recently completed Transit Cooperative Research Program (TCRP) project analyzed the reasons for this decline [2]. Using bus and rail ridership data along with several descriptive variables from 215 Metropolitan Statistical Areas (MSAs) in the U.S. between 2012 through 2018, the study finds that the traditional factors like increase in public transport (P.T.) fares, inexpensive gas along with rising income levels, increased car ownership, and shift to Work-from-Home (WFH) culture have resulted in a net 4% decrease in transit ridership. The study finds modes like ride-hailing services the single biggest reason for declining ridership over this period, contributing a net 10% to 14% decrease in MSAs having annual transit operating expenses between \$30 to \$300 million [2]. Other emerging modes like bike shares (public bike-sharing schemes) and e-scooters have minimal impact. Given that public transportation usage is essential for achieving societal, economic, and environmental goals, this declining ridership trend presents a severe challenge for many cities.

Transit operators and cities are considering a range of strategies in response to declining ridership. Some operators are re-thinking their mission and metrics for service delivery to consider the weight placed on maximizing ridership in the densest corridors versus providing service to those who rely on transit the most [3]. Depending on that balance, transit operators might consolidate service onto a smaller number of high-frequency routes or focus specifically on serving low-income riders and essential workers. Either strategy can be combined with exclusive right-of-way for transit, bypassing traffic and giving it a travel time advantage. Other transit agencies are considering a range of fare policies and pricing incentives to lure riders back to transit. Some operators are entering partnerships with other mobility providers, although these should be carefully considered to ensure they are working in the best interest of the transit operator and riders.

While agencies may wish to evaluate such strategies based on local context and conditions, there is value in understanding which holds promise for further study. This paper considers three potential strategies for one small and one large city in the U.S. and measures their expected effect on transit use. The three scenarios are:

1. **Low-Income riders focus:** improve services on the transit routes with a larger share of low-income households, thereby improving access to these groups that rely on transit service.
2. **High-Ridership route focus:** improve services on routes with the highest transit patronage, speed up transferability, and reduce overall travel time.
3. **High-Ridership route focus with Exclusive Bus Lanes (EBL):** introduce exclusive bus lanes on the transit routes identified in the previous scenario, thus ensuring reliable and high-frequency transit services. It would make transit a viable, cost-effective, and efficient alternative to a private mode of transport.

We test each scenario for the Oshkosh, Wisconsin, and Atlanta, Georgia areas. We do so using CityCast, a commercial data-driven tool designed to help transport modelers and planners test various strategies and their impacts. We apply CityCast in combination with the Multi-Agent-based Transport Simulation (MATSim) [4]. MATSim is an open-source simulation framework that allows explicit simulation of the multi-modal public transportation system. Together these tools replicate the observed travel patterns in those areas and simulate their movement through a transportation network (either the existing one or a hypothetical one), selecting modes and routes that best serve their destinations.

The paper is structured as follows: Section 2 presents the overview of the modeling framework. Section 3 defines the scenarios tested in this study and cities and the data we use to run such simulations. Section 4 presents the analysis of simulation study results and is finally generalized and discussed in Section 5.

LITERATURE REVIEW

Changing the amount of service provided in different areas of a city has long been a strategy used by transit agencies to improve ridership. TCRP Research Report 209 presents strategies that transit agencies can consider to increase transit ridership [5]. According to the report, undertaking service level improvement remains the first choice of transit operators, given that ridership is sensitive to the service levels, reliability, and fares [5]. Seattle stands out from other implementations as it witnessed a 1.3% increase in bus ridership and a 74% increase in light rail transit (LRT) ridership between 2014-2016 [5].

Considered as the "Hottest Trend in Transit" [6], network restructuring is another re-design strategy which many transit agencies have adopted to prioritizes service concentration (higher frequency) over coverage. Transit agencies of Connect Transit in Bloomington-Normal, IL, Central Ohio Transit Authority (COTA) in Columbus, and MDOT Maryland Department of Transportation's Maryland Transit Administration (MDOT MTA) have successfully implemented such bus network redesigns [7]. Since its implementation by August 2016, Connect Transit in Bloomington-Normal, IL, has witnessed a steady rise on routes that have headways of 30 minutes or better. According to COTA, the restructuring in Sep 2017 allowed them to slow the rate of declining ridership, while MDOT MTA did not witness any changes in ridership [7]. However, it must be acknowledged that all three transit agencies coupled their network restructuring strategy with increased operating budgets.

Few transit agencies have invested in inter-and intra- (transit modes) connectivity strategy as part of improving transit ridership. For example, in Minneapolis, the transit agency reduced bus routes whose services would be affected by the new LRT system, "Metro Green Line train" [5], [8]. These freed-up resources that could be distributed on bus routes connecting LRT lines to improve coverage, frequency, and service hours. As a result, ridership on LRT reached 37,400 for 2015, closer to Metro's goal of 41,000 by the year 2030. The bus transit ridership nearly doubled along the Minneapolis central corridor [8].

Similarly, statistical analysis exploring factors affecting public transport ridership at the city- or multicity-scale and transit route level could also be found in academic literature [2], [9]–[11]. However, these studies are based on before-after analysis and lack providing transit agencies a tool to "systematically" investigate how and to what extent a transit strategy could affect network performance and travelers' decisions.

Given the size and the complexity of the public transportation system, the risk involved, along with financial and time constraints, it is impossible to implement a new solution directly without investigating the efficiency and effectiveness of the service provided. Transit agencies, therefore, often utilize transport models to support their decision-making. Studies focusing on transit signal priority, operation of bus stops, and bus lanes are found in the transit simulation literature, and their recommendations are useful [12]. However, such simulations results are microscopic in perspective, focusing only on one specific transit mode without taking interaction with other modes into account. In urban settings, buses and streetcars often share road infrastructure with car traffic, and it is simply impossible to view the transit systems in isolation.

Furthermore, traditional flow-based transport models are aggregate models that cannot distinguish between large personal groups and capture and present time-dynamic results. Macroscopic simulation models like MATSim have been developed to overcome these limitations [13]. These models capture the dynamic interactions between general (car, bicycle) traffic, transit vehicles, and passengers in the urban or regional context in an integrated way [13]. Although MATSim takes much longer to compute than traditional assignment models, it delivers more detailed interaction between users, vehicles, and road infrastructure, thereby providing value to transportation planners and policymakers regarding the effect of studied operational strategies and demand management schemes.

For example, the Go To 2040 document of the Chicago Metropolitan Agency For Planning (CMAP) evaluated various transit strategies to understand their impacts on transit ridership [14]. Table 1 summarizes the results of the relevant scenarios studies undertaken to explore transit-supportive policies using CMAP's regional and activity-based travel demand model.

Table 1: Transit Strategies evaluated by CMAP (results adapted from CMAP's Go To 2040: Transit Growth Study)

Sr. No	Transit Strategy evaluated	Study result
1	expanding rail network - two rail extensions - five line improvments	- mode share would merely increase by 0.29% - strategy is expensive to introduce - accessibility of jobs increased with 75-minute transit trip limit - almost all new trips were "work" trips - attracted more riders from "bus" than "car"

2	New bus services (on six highest-ridership route) in the form of - Bus Rapid Transt (5min headway) - Arterial Rapid Transit (10min headway)	- transit mode share increase by 0.17% - attracted high percentage of new riders - improved average commute time - no effect on congestion - reduction in auto VMTs
3	differentiated transit fares - 10% hike in peak period - 10% off in non-peak hours	- 0.11 to 0.70 % increase in transport share - decrease in "work" trips by transit however compensated by new "non-work" trips during off-peak hours - increase in auto VMT - fare revenue marginally decreaed by 3%
4	increase in bus transit services, two scenarios - high alternative: 50% reduction in headways leading to doubling of offered service hours - low alternative: 25% reduction in headways leading to 33% more service hours	- transit share grew by 1% & 0.43% for high and low alternative scenario respectively - low ridership routes tended to show larger percentile increment than high-ridership routes
5	Improving transit availability where the coverage is low	- ineffective from transit ridership perspective - less cost-effective because of more overhead cost

Similarly, Ben-Dor et al. [15] examined the qualitative effects of dedicated bus lanes (DBL) on bus transit performance, travel time, and congestion using MATSim. Using data from Sioux Falls, South Dakota, the study found that the addition of DBL can improve transit ridership in the range of 10 to 20% depending upon the level of congestion observed during peak hours [15]. Other examples of public transportation simulations conducted using MATSim include Berlin, Switzerland, Singapore, and New York [4], [16], [17]. However, route-level ridership modeling has rarely been explored using MATSim or public-transport simulation literature [4], [11]. Our study aims to fill the gap by developing transit scenarios and understanding their impacts on route-level ridership.

METHOD

We tested each scenario for two cities using a modeling framework that uses CityCast in combination with MATSim. Together the tools simulate the ridership changes expected from each scenario.

CityCast

The paper relies on the data obtained from CityCast, a commercial data-driven tool designed to help transport modelers and planners test various strategies and their impacts [18]. CityCast is an online web-based travel demand modeling platform that utilizes passive data collected for a large proportion of the population, capturing their travel activities via location data shared with applications on their mobile devices. Predominantly CityCast uses data gathered from commercial consumer data sources, firm data sources, mobile phone location data, transit network information via General Transit Feed Specification (GTFS), U.S. Census data, and National Household Travel Survey (NHTS) data. These data are fused to create one sizeable comprehensive dataset that synthesizes daily itineraries for a synthesized population. This synthetic population represents the actual characteristics of the region. The main output of CityCast is a list of simulated travelers, their location and preferred timing of the activities they participate in, and the trips between those activities. The output resembles the data obtained from a household travel survey but for a synthetic population instead of a sample of the entire population. It is also similar in format to the demand generated from an activity-based travel model. There are two reasons we prefer CityCast for this application: 1) it is generated directly from observed travel patterns (in the form of location-based services data), and 2) it is implemented using a standardized process that is available in any location in the U.S. The simulated population containing trip information in the form of travel diaries is then assigned to the transport network using MATSim, which determines the mode, route, and departure time of each trip. The CityCast web interface facilitates running MATSim for users on cloud infrastructure, but in this study, we ran MATSim locally to allow for finer-grain control of settings.

MATSim

MATSim is an agent-based transport modeling framework and is used to simulate large-scale scenarios. Central to MATSim's framework is its agents, which represent real-world individuals. Each agent is free to make decisions to maximize their transport. MATSim simulates these individual agents' travel plans on a detailed transportation network for 24 hours (or more). This travel plan contains a detailed schedule of individual agents' movements, including the activity location, types of trips made, modes used, and the time spent to travel from one point to another. The model records the interaction between multiple agents who simultaneously try to move across the transport network in space and over time, including the start time of the trip journey, facility origin and destination, agent identifier, traversed road segment identifiers, including time of entry and exit, the transport mode used, and boarding and alighting stops. These details are utilized for further analysis.

MATSim adopts a first-in-first-out (FIFO) queueing model to resolve traffic flow dynamics on each street segment. To choose the best way to travel between activities to accomplish agents' skeletal activity plans, MATSim tries different combinations of modes, traversed paths, and departure times and assigns a score to each attempted plan for each agent. The concept of scoring is similar to the utility function used in the traditional transport modeling framework, which allows modelers to capture the agents' preferences. The replanning, where new combinations are generated, and the simulation of those plans is a recursive process and repeats until the agents can no longer improve their travel scores, thus signifying user equilibrium (U.E.) status. At this stage, the average population score takes the form of an evolutionary optimization progress curve [19], [20], suggesting that the final iteration's output plans can be further analyzed. In our study, this was achieved on the 50th iteration run.

At a minimum, a MATSim simulation needs 1) network data reflecting current physical infrastructure conditions and transit service on that infrastructure (if service exists), 2) initial activity skeletons of all individual simulated travelers (also termed as "agents"), and 3) configuration parameters. GTFS data, which is freely available for selected cities, is used to generate the transit service [21]. The service is made up of schedules and vehicle information, which allows us to model all available public transportation modes, dimensions of each vehicle type, and passenger car equivalent (PCEs). In the MATSim framework, each departure in the schedule gets mapped to a different vehicle.

Further information regarding installation, setup, and analysis of MATSim can be found in its handbook [4].

Scenario Generation

This study focuses on improving service quantity to increase the total transit ridership across the city.

- *Base scenario*: Before the developed scenario is tested and simulated, a base condition representing the city's current transport condition, including traffic flow, congestion, and transit ridership, is modeled. The base case scenario is generated using 2019 (pre-COVID19 restrictions) data and therefore reflects pre-pandemic traffic conditions.
- *Low-income riders focus*: The overall goal of this scenario is to improve access to transit services of low-income households. We identify the top 20% of the bus transit routes that carry the highest share of low-income household riders. We define low-income households as those with less than $20,000 in annual income. We double the frequency on these identified transit lines while reducing on remaining routes to maintain the same VRM.
- *High-ridership route focus*: The overall goal of this scenario is to further improve services on transit lines that have the highest ridership. We identify the top 20% of the bus transit routes that carry the highest number of passengers. We doubled the frequency on these transit lines while reducing on remaining routes to maintain the same VRM.
- *High-ridership route focus, with Exclusive Bus Lanes (EBL)*: Building upon the previous scenario, frequency on the top 20% transit service with the highest number of riders is doubled, with services reduced on remaining routes to maintain the same VRM. In addition, the provision of dedicated road infrastructure is in the form of exclusive bus lanes (EBL) on these top 20% of transit routes. We assume that these bus lanes are new additional capacity with no decrease in existing roadway capacity.

Selected Cities

Oshkosh, Wisconsin

With around 400,000 population, the Oshkosh-Neenah, WI MSA is served by two transit agencies. The Oshkosh Transit System (Go Transit) serves the Oshkosh area, while the Neenah-Menasha area gets served by Valley Transit [22]. The Oshkosh Transit System has nine routes, with buses running from 6:00 am to 6:00 pm. They also operate a route that connects Oshkosh to Neenah to allow residents to expand their employment opportunities and cultural and shopping activities.

Compared to Atlanta, the topography and transit operation in the Oshkosh area is relatively small and straightforward and therefore is appealing to our study as it helped us evaluate and directly compare strategy results to other cities.

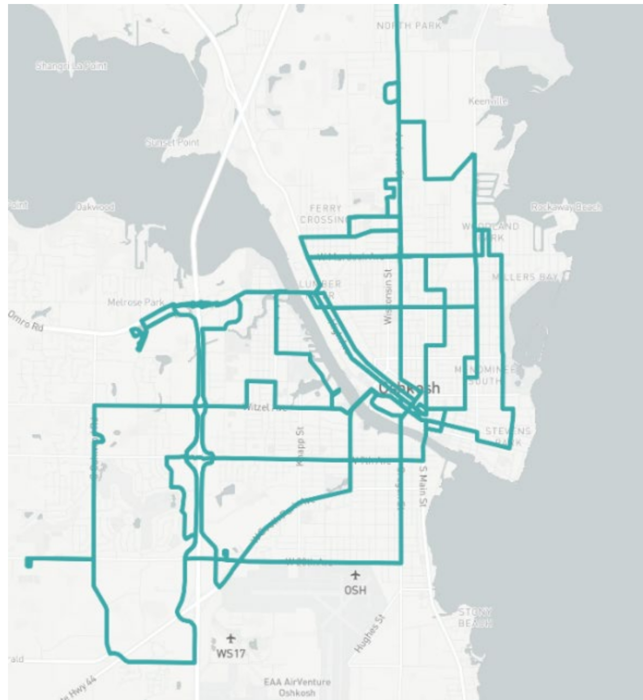

Figure 1: Overview of transit routes in Oshkosh, WI (image source: CityCast web interface)

Atlanta, Georgia

Metro Atlanta is the ninth-largest metropolitan statistical area (MSA) in the United States and the most populous metro area in Georgia, with an estimated 2017 population of 6 million [23]. Public transportation consists of rapid rail (76.6km, shown in red, dark blue, green, and gold line), Atlanta StreetCar (4.3km, coded in purple line), and bus-based services (coded in light blue colored lines). Metropolitan Atlanta Rapid Transit Authority (MARTA) runs most of the region's rapid rail and bus transit system. Other counties in the MSA also provide local bus routes in and out of Atlanta downtown (not differentiated in the figure). Further, the Georgia Regional Transportation Authority (GRTA), a state-owned agency, operates regional commuter Xpress bus routes (not shown in the figure), primarily into Downtown Atlanta. Thus making the Atlanta transport system an exciting case study for the analysis of alternative transport policies.

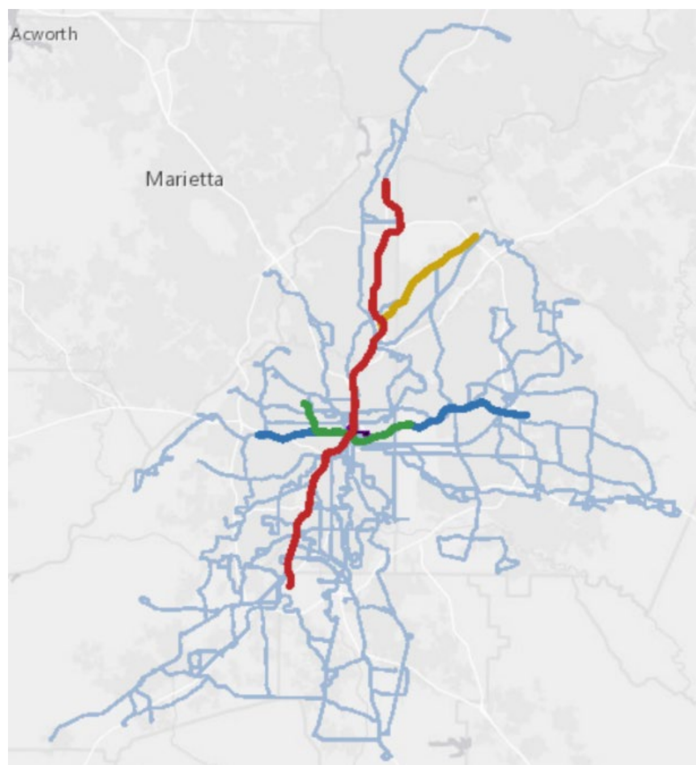

Figure 2: Overview of transit routes in Atlanta, GA

Unlike Oshkosh, having both rail-based and bus-based transit systems makes the Atlanta transit system much more complex to operate and maintain. Given that the timetable of bus-based transit is much easier to reconfigure than rail, the study sought to demonstrate changes to only bus-based transit service schedules. Furthermore, instead of identifying the top 20% of transit (bus) lines across the whole network, the study selected 20% of transit (bus) lines from each operator's routes. It allows the network level changes to be dispersed uniformly at the operator's level.

Table 2 presents other relevant details related to the cities for the baseline scenario.

Table 2: Other relevant details related to cities for the base scenario

	Oshkosh, WI	Atlanta, GA
Demographics		
Number of households (sampled/synthetic population)	1,592,02	4,567,93
Number of people (sampled/synthetic population)	3,812,12	1,159,187
Road Network		
Number of links	71,462	1,202,783
Number of nodes	29,993	540,655
Public Transport Services		
Number of Transit Routes	15	307
Number of departures	372	11,665
Number of transits stop facilities	259	10,421

RESULTS

Here we present several critical indicators from the results of each city.

Changes in transit ridership

Table 3 presents the summary snapshot of the percentage change in bus transit ridership across the city from the baseline condition. Overall, except for Oshkosh's low-income riders focus, the bus transit ridership has positively increased irrespective of the scenarios developed. The decrease in ridership observed in Oshkosh's low-income riders scenario is due to changes (reduction) brought in frequencies of other transit routes to increase transit services on routes catering to the highest share of low-income households. Variability in ridership indicates that other transit system characteristics like accessibility, route density, transit waiting time, and (low) population density also influence total system ridership [25], [26].

Furthermore, we also find an increase in low-income riders in the high-ridership route focus and high-ridership route focus with EBL. It indicates that given the size and demographics of Oshkosh, low-income households are the ones who are primary users of public transport. Therefore, any increase in bus transit service frequency along the main routes increases the ridership among low-income household riders. Like Oshkosh, in Atlanta, the highest ridership routes carry the highest percentage of low-income riders even though the share of low-income riders compared to total ridership may be lower.

Table 3: Percentile changes in transit ridership w.r.t base scenario

	Oshkosh, WI		Atlanta, GA	
Scenario	**Total Riders**	**Low-Income Riders**	**Total Riders**	**Low-Income Riders**
Low-income riders focus	-1%	-3%	44%	47%
High-ridership route focus	30%	39%	88%	70%
High-ridership route focus, with EBL	31%	37%	109%	89%

The geographic spread of the transit ridership

Figure 3 and Figure 4 present the spatial spread of bus transit ridership by Census Tract for the base scenario for Oshkosh, WI, and Atlanta, GA, respectively. The radius of the circle corresponds to the total number of transit riders. The blue circle markers in Figure 4 corresponds to total rail-based transit riders, while pink circle markers represent total bus-based transit ridership in a given Census Tract.

For Oshkosh, the census tracts with the highest bus transit ridership are adjacent to the riverside and city center. The city center consists of Downtown Transit Center from where the majority of the bus services originate or terminate, with the University of Wisconsin-Oshkosh premise located NorthEast side to it. For Atlanta, the rail ridership is exceptionally high in the downtown area and going up in the northwards direction of the MARTAs red line. MARTA red line (subway) traverses through the north and south of Atlanta, covering downtown Atlanta, Midtown, Buckhead, and Hartsfield-Jackson International Airport. Red lines rail stations are located near major business centers, hotels, restaurants, commercial offices, and tourist attractions, attracting high footfall of pedestrians.

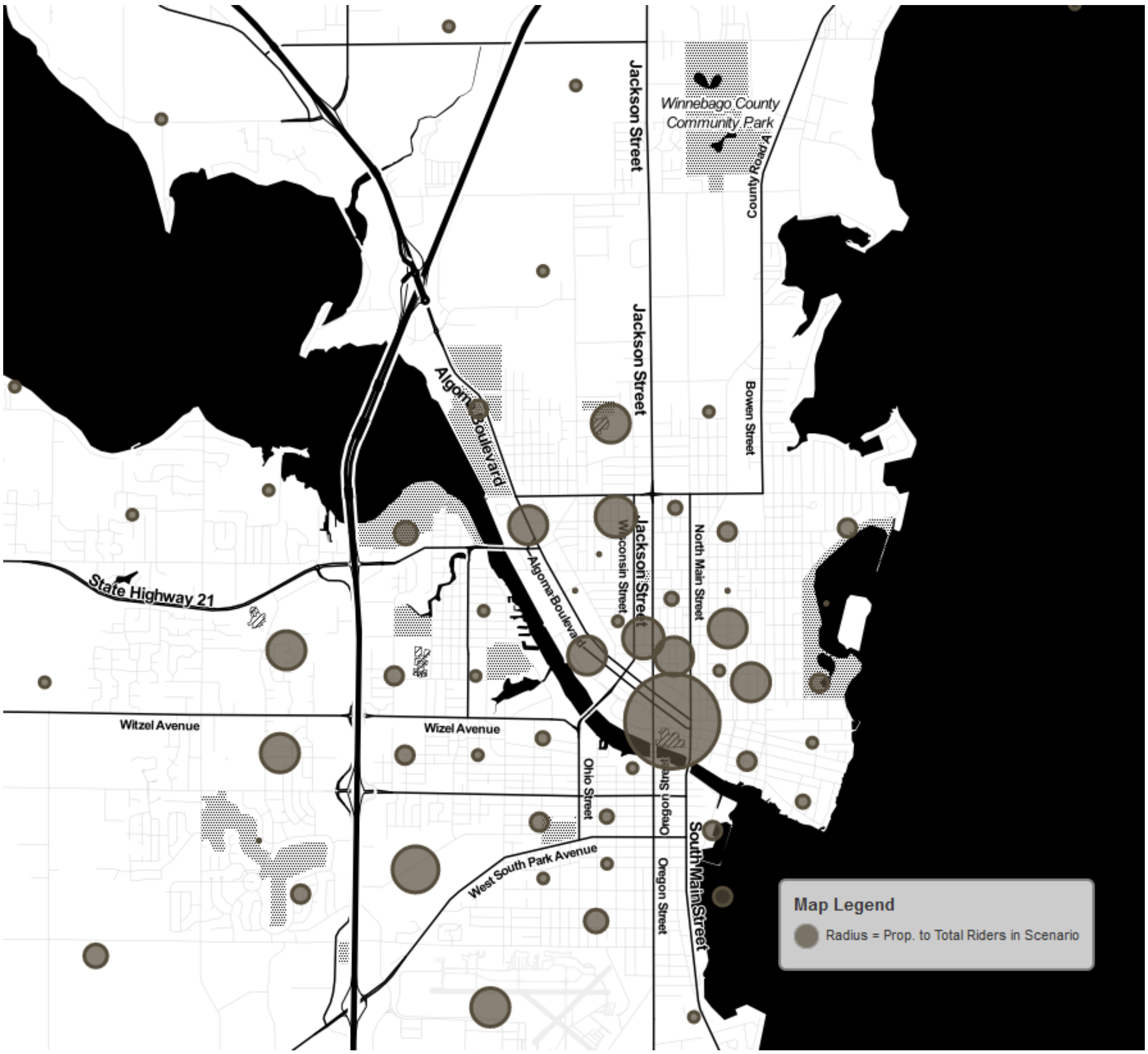

Figure 3: Transit - Bus ridership across Census Tract for Base Scenario, Oshkosh, WI

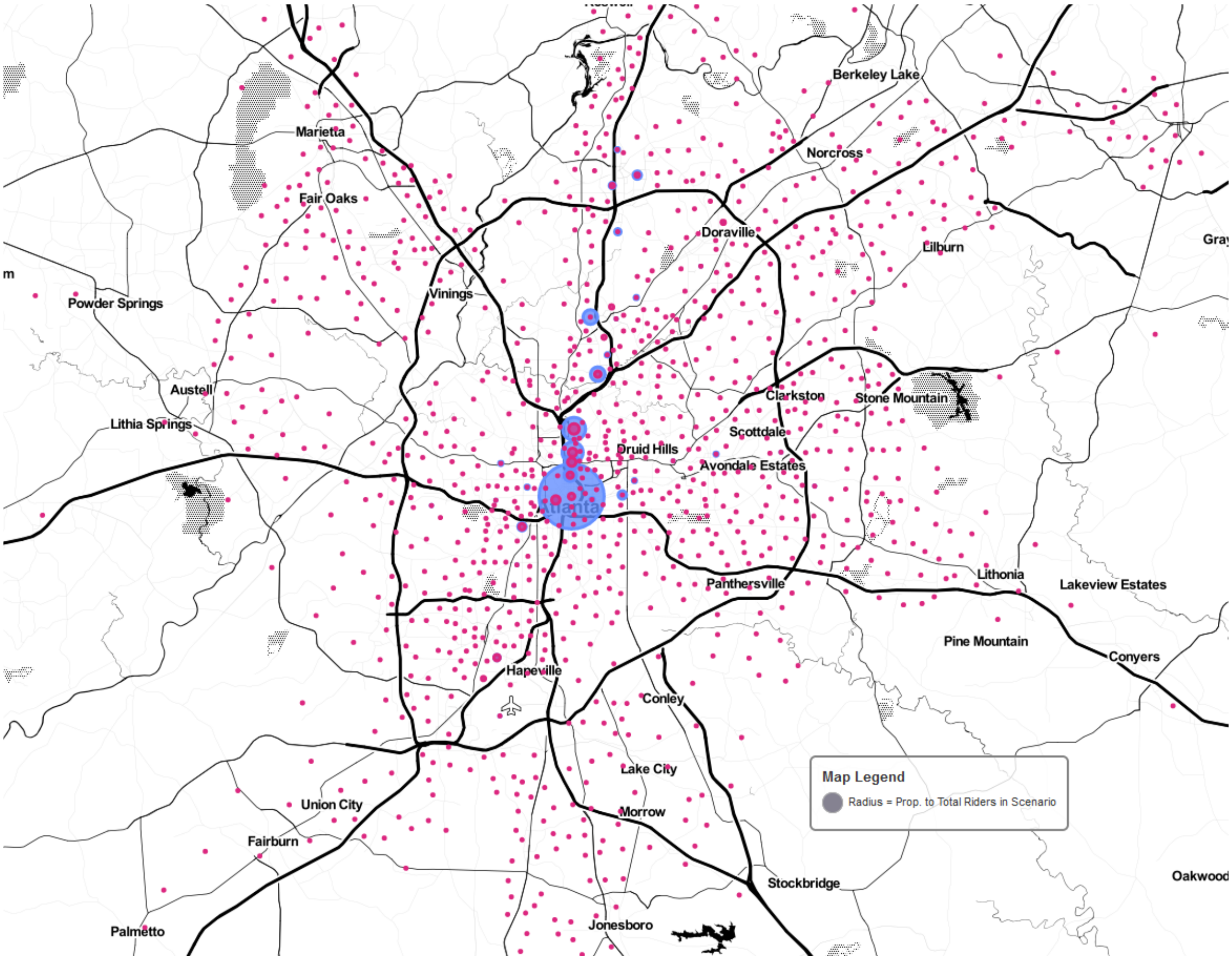

Figure 4: Transit – Bus & Rail ridership across Census Tract for Base Scenario, Atlanta, GA

Figure 5 through Figure 10 present the distribution of the transit ridership spatially by Census Tract compared with baseline conditions for both cities. The radius of the circle marker is proportional to the absolute change in the number of riders. The color of the circle marker represents the percentile increases or decreases in transit ridership going from baseline to given strategy scenario, with green colors indicating higher ridership and red colors indicating lower ridership.

In Oshkosh, we observe that the Low-income riders focus scenario (Figure 5) increases ridership west of the river and decreases ridership north of the river. The High-ridership route focus (Figure 8Figure 6) and High-ridership route focus, with EBL scenarios (Figure 7), do the opposite. The Oshkosh downtown is just north/east of the river. This spatial pattern reflects the difference between those routes more directly serving downtown that have the highest ridership and those routes to the west that have lower overall ridership but a higher share of low-income riders.

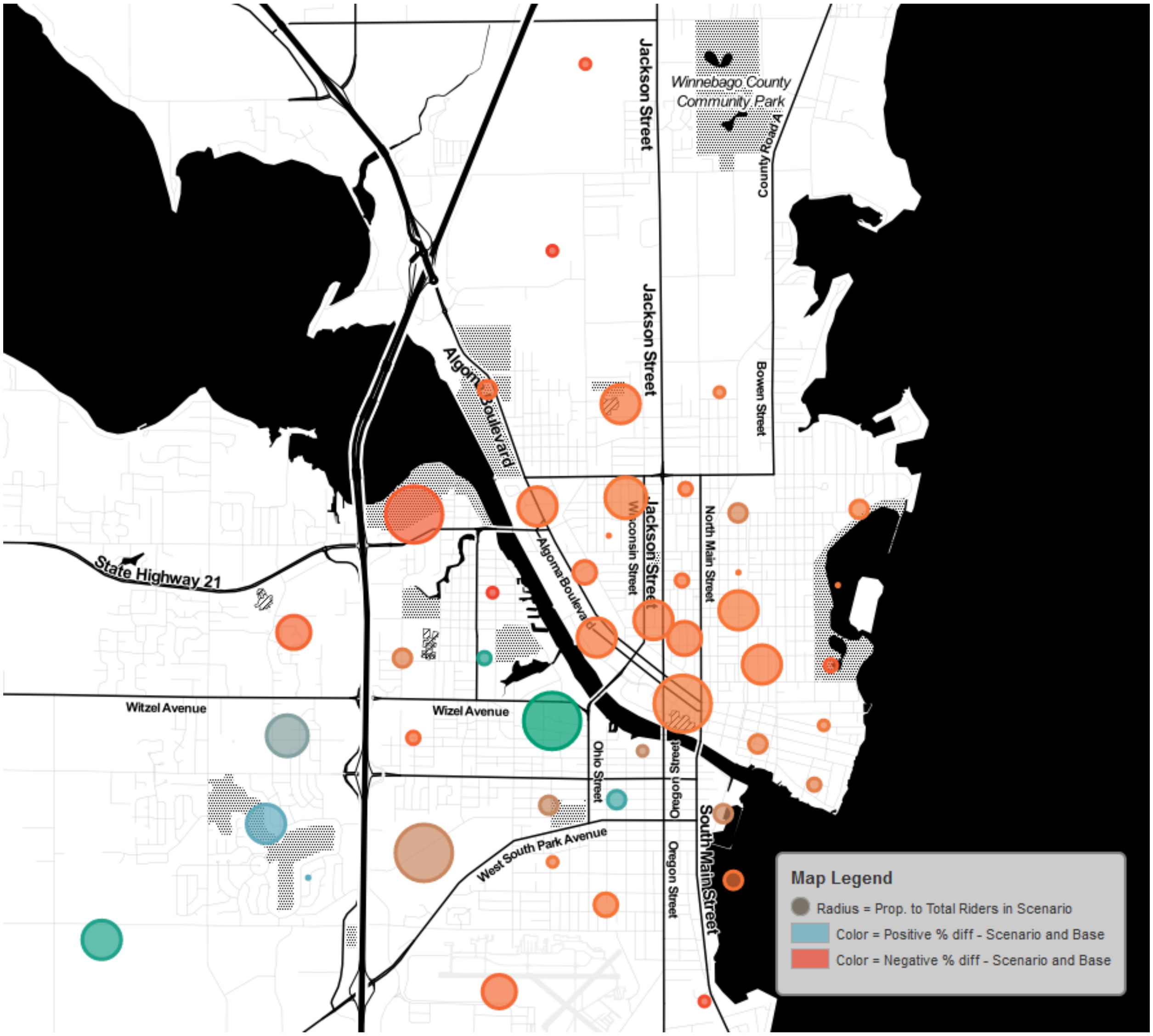

Figure 5: Change in bus ridership by Census Tract for low-income riders focus scenario, Oshkosh, WI

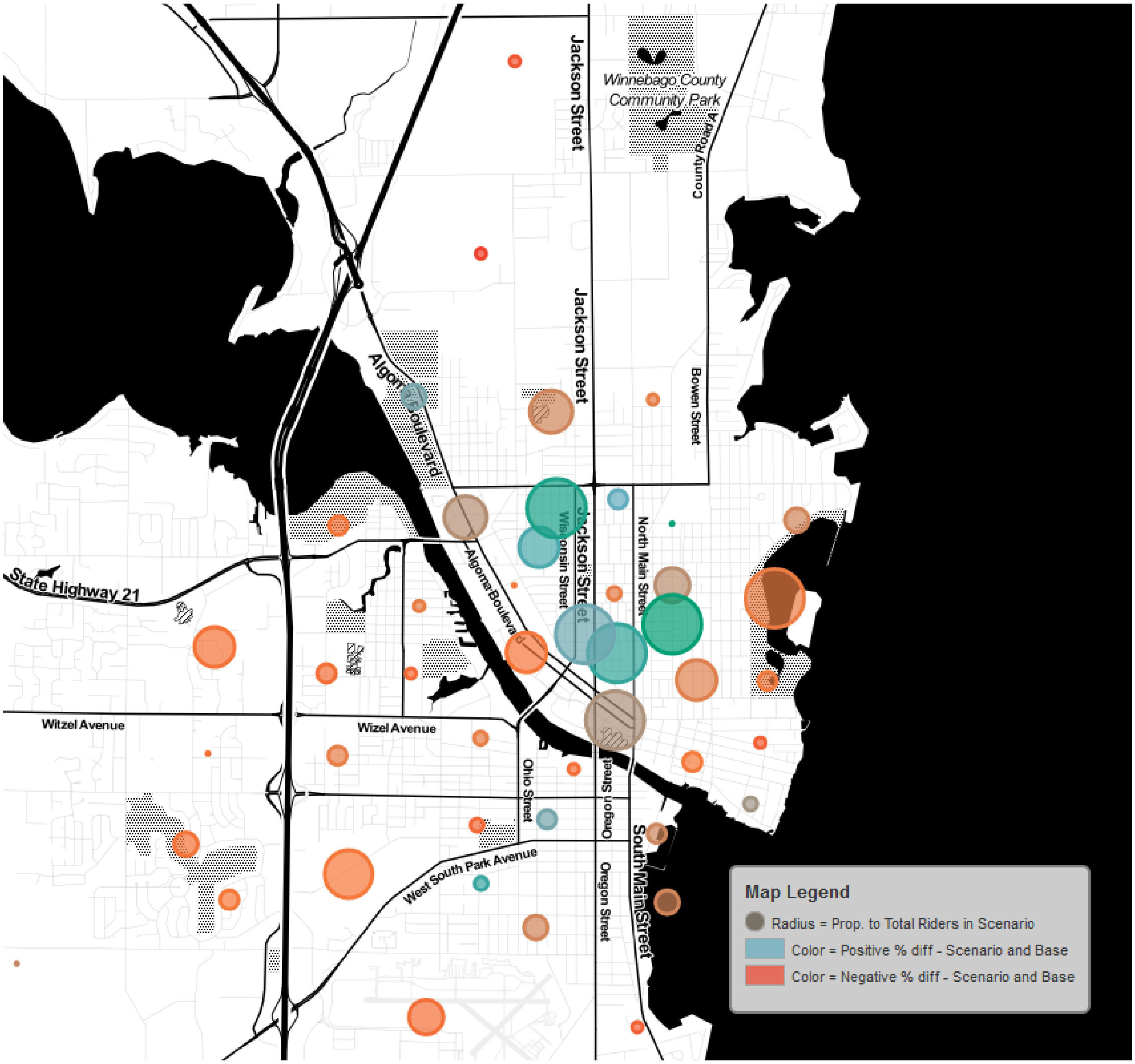

Figure 6: Change in bus ridership by Census Tract for high-ridership route focus scenario, Oshkosh, WI

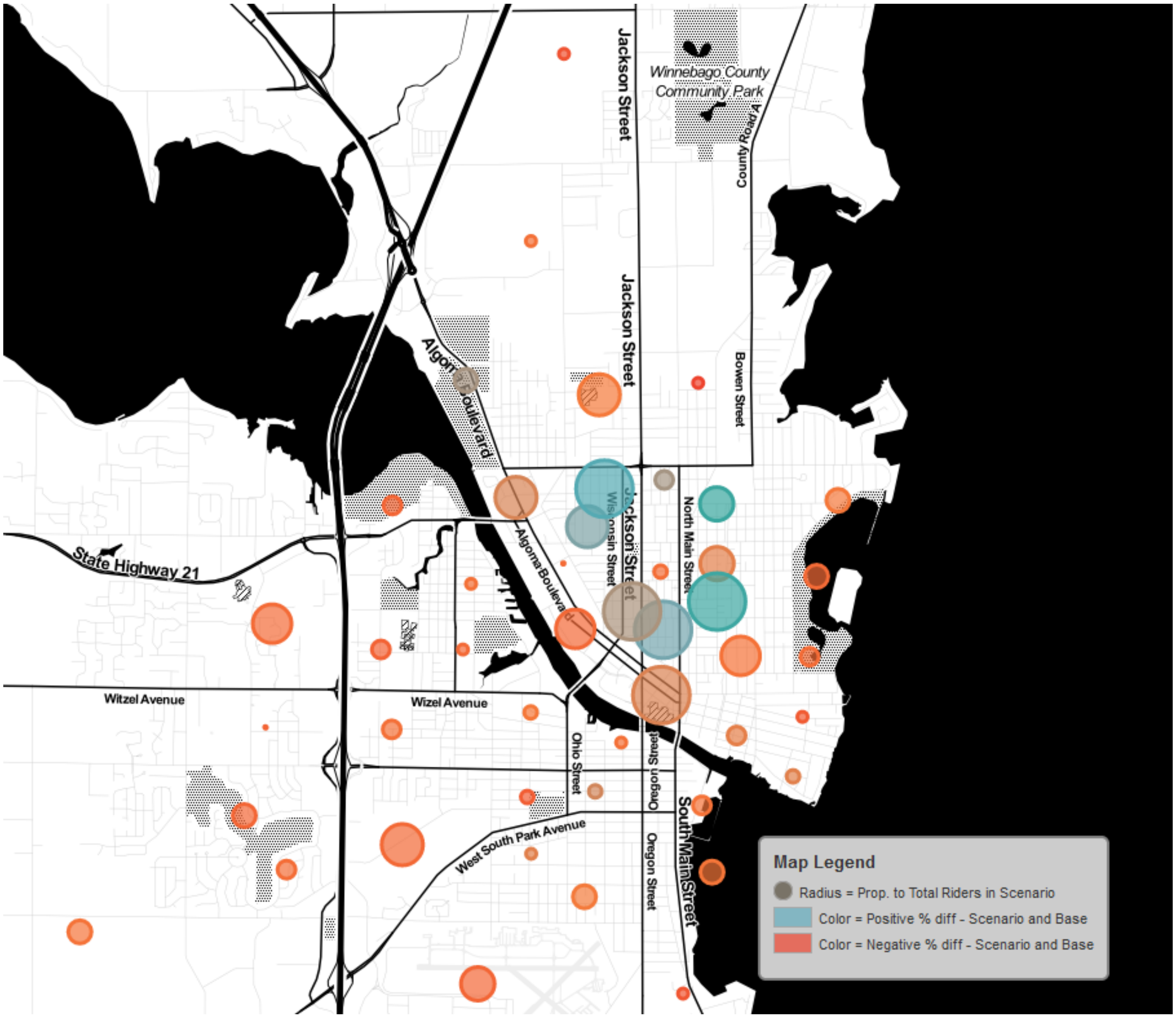

Figure 7: Change in bus ridership by Census Tract for high-ridership route focus with EBL, Oshkosh, WI

In Atlanta, the low-income ridership (Figure 8) gains are primarily concentrated west of I-85, with losses east of I-85 but within the perimeter of I-285. In the high-ridership route focus scenario (Figure 9), north of I-20 gains ridership while south of I-20 witnesses losses. Interestingly, the area near the south side of Atlanta loses ridership for the high-ridership focus scenario but gains riders for the high-ridership focus with exclusive bus lane scenario (Figure 10). These spatial differences reflect Atlanta's demographics spread and point to the locations where the low-income and minority travelers either start or terminate their transit journey. As transit-rail ridership has not significantly changed between the base case and developed scenario, the blue markers representing them are not distinguishable or identifiable. Rings (dark blue) like markers are visible around the North and South of the downtown area of Atlanta; however, their occurrence is somewhat limited in numbers.

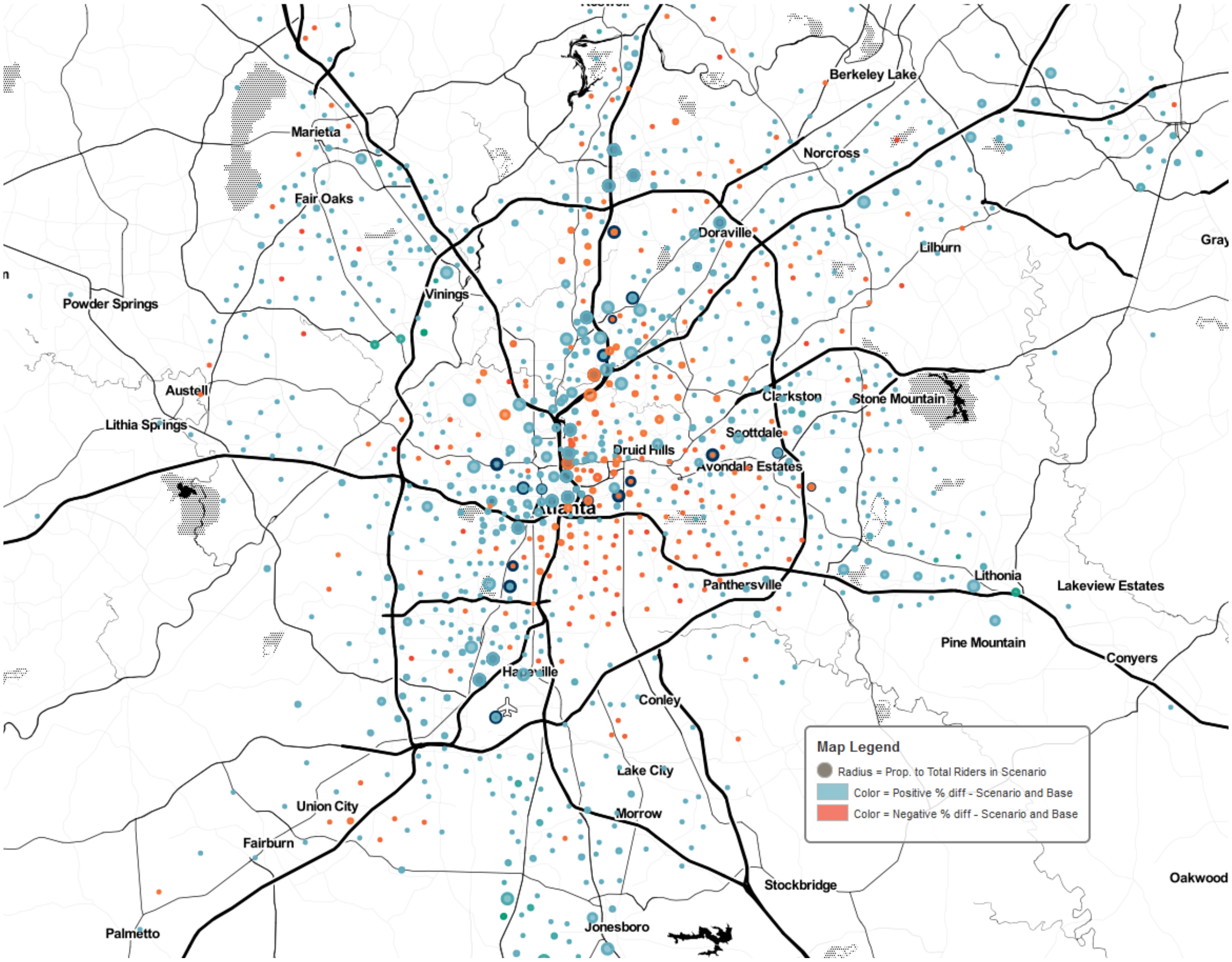

Figure 8: Change in bus ridership by Census Tract for low-income riders focus in Atlanta, GA

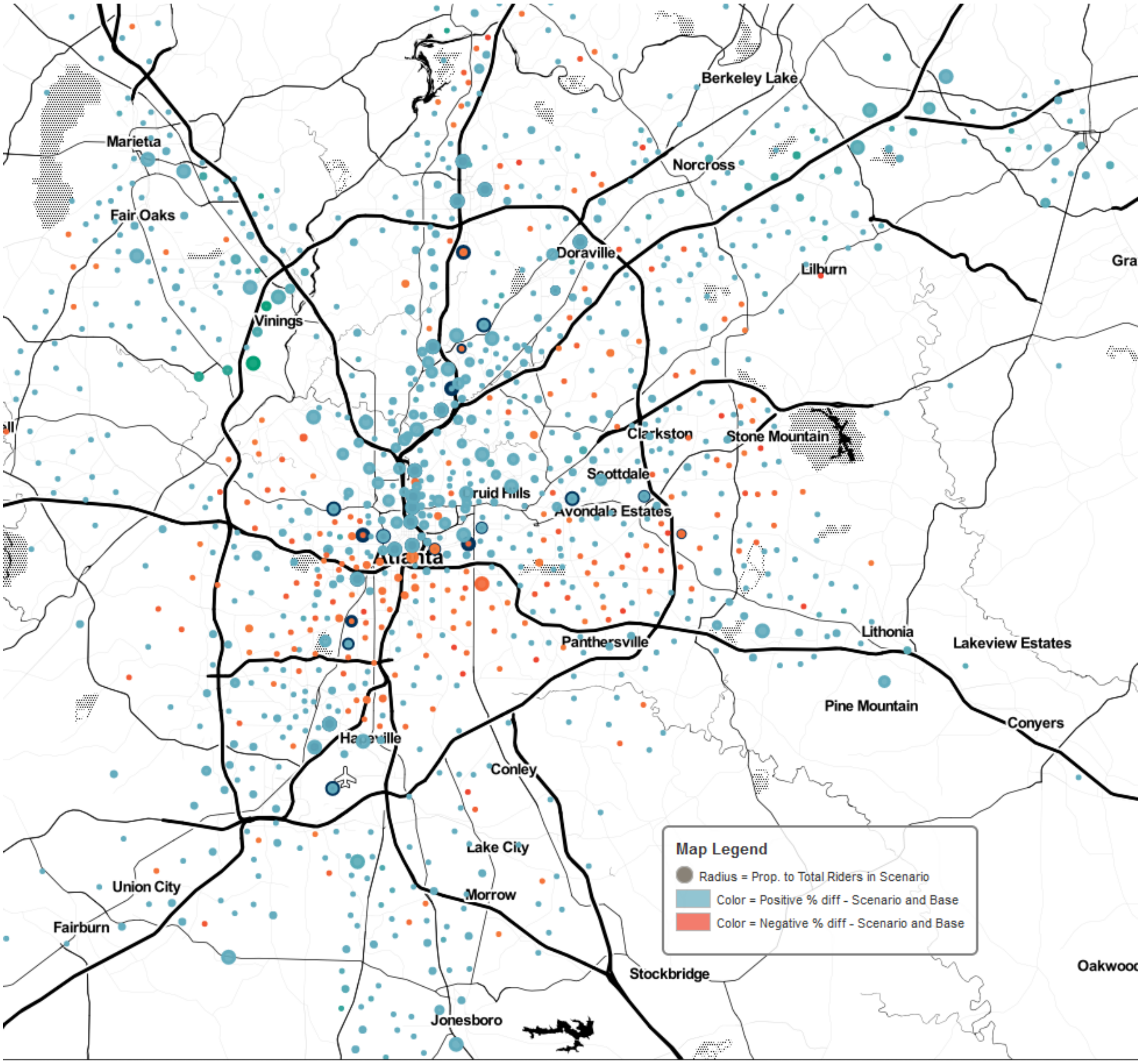

Figure 9: Change in bus ridership by Census Tract for high-ridership route focus in Atlanta, GA

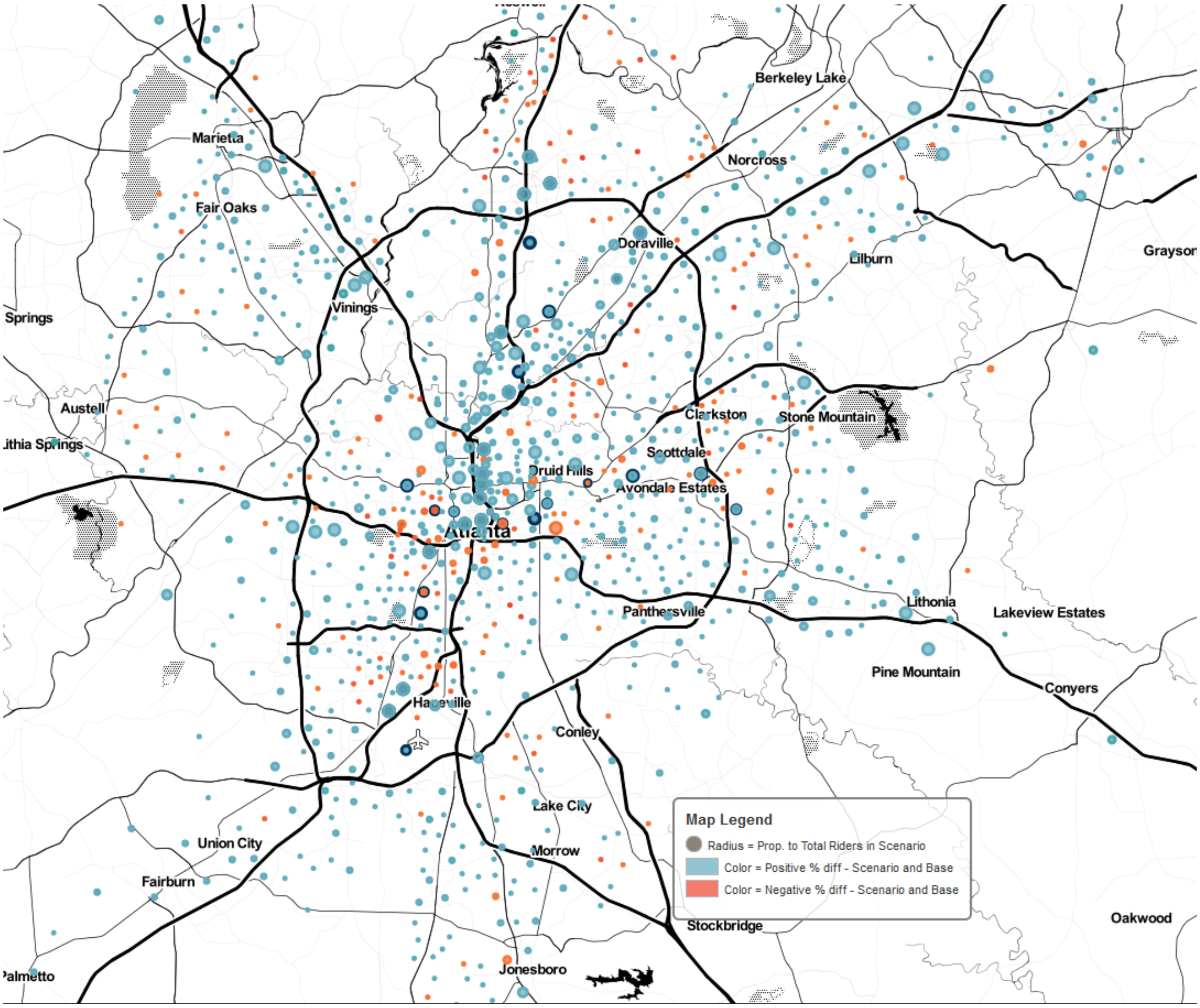

Figure 10: Change in bus ridership by Census Tract for high-ridership route focus with EBL in Atlanta, GA

DISCUSSION AND SUMMARY

In this paper, we explored three strategies that transit operators may consider to increase ridership: consolidating service on bus routes serving the highest share of low-income riders, consolidating service on those bus routes with the highest ridership, and consolidating high-ridership bus routes in combination with giving those routes exclusive bus lanes. In each scenario, we double the service frequency of buses on the focus routes and reduce the frequency on all other routes to maintain the exact total vehicle revenue miles. In this way, we expect all three scenarios to be roughly operating-cost neutral. We tested these scenarios for Oshkosh, Wisconsin, and Atlanta, Georgia, using a modeling framework that combines CityCast to replicate observed travel patterns and MATSim to simulate how travelers would change the route, mode, and time-of-day of the trips they make in response to the service changes.

The results show:

- The Low-income riders focus scenario increases overall bus ridership in Atlanta by 44% and low-income household ridership by 47%. However, it results in a slight ridership decrease in Oshkosh (-1% and -3%), respectively, mainly because the ridership losses on the routes where ridership is cut offsets the gains on streets with increased service. The difference in results for the exact scenario implementation in Atlanta indicates that such changes may not always result in overall ridership increases and that the effective design also depends upon the local conditions.

- The High-ridership route focus leads to ridership gains for both urban areas, with a 30% bus ridership increase in Oshkosh and a 88% bus ridership increase in Atlanta. The number of low-income bus riders increases more than in the Low-Income rider focus scenario. This change occurs because the high-ridership routes often have a large absolute number of low-income riders, whereas we defined the Low-Income rider focus scenario based on the share of low-income riders. This result highlights how the metrics we choose—percentage versus the absolute number of low-income riders—can affect transportation outcomes. It also highlights that the goals of serving disadvantaged riders and of increasing ridership are not necessarily mutually exclusive.
- The introduction of exclusive bus lanes (EBL) on the High-ridership routes, as identified in the previous scenario, increases the bus transit ridership in Atlanta but not in Oshkosh. Such contradicting results occur because Atlanta is more congested, such that additional bus lanes can offer a more significant travel time advantage.

These results are logical in the direction and the relative ordering of the ridership effects, although we found the high magnitude of the ridership gains surprising given that the overall service levels were held roughly constant. While such large ridership jumps have been reported in the past [27], [28], their occurrence is rare. The elasticity of bus ridership to changes in frequency is estimated to be in the range from 0.66 to 0.78 [10], meaning that increasing frequency by 10% would increase ridership by 7%, on average, which is far less than what we observe in our simulated cases. Higher ridership jumps may arise due to increased frequency levels limited to most productive routes compared to overall transit service in general. However, such observed simulation's sensitivity to transit service changes warrants further investigation. For example, in our application of MATSim, we do not account for constraints or different scoring by auto ownership, so it may be that the simulation is too willing to shift travelers with a vehicle from car to transit.

Conversely, we made two assumptions that could potentially under-estimate the benefits of the exclusive bus lane scenario relative to the others. On congested roads, exclusive bus lanes can increase the travel speeds by 60% over the baseline scenario [29]. In addition, if the lane is converted from a general-purpose lane, congestion may worsen for cars, resulting in a more significant relative benefit for transit. Our simulation assumed that the exclusive bus lanes were new capacity (we did so to avoid troubleshooting potential network coding errors), so car travel times are likely faster than they would be if existing road capacity were reallocated. In addition, a second advantage to exclusive bus lanes is that the bus gets to the end of its route faster, allowing it to run the reverse route more quickly. Therefore, exclusive bus lanes allow for more frequent service with the same number of vehicle revenue hours.

The ongoing COVID-19 pandemic has affected people's travel behavior in many ways. This study, along with its data, reflects pre-pandemic conditions. As the pandemic spread across American cities, “stay-at-home” orders along with social distance measures were implemented, requiring many public services, retail businesses, and tourism spots to be shut down or run on minimum capacities. Such abrupt closures not only halted the economic activities of cities but have changed people’s travel behavior. For example, in April 2020, both New York’s (NY) subway and bus transit services reached unprecedented low points, down by 92% and 77% compared to the year 2019 ridership. By the end of 2020, they slowly recovered to 50% and 31% of 2019 ridership [30]. As of July 2021, NY subway and bus service ridership continues to be -54% and -47% compared to 2019 data [31]. The results mirror the post-COVID study from Shenzen, China, which showed that people are hesitant to use transit and prefer continuing to drive cars [32]. At the same time, other traffic modes such as cycling and walking have grown dramatically [32]. Because of changing preferences, we may not see a full recovery of the mode share to pre-COVID levels. Hence, existing data must be recalibrated to represent the travel behavior during and after the COVID-19 pandemic.

Despite these limitations, our study suggests that transit operators may have room to increase ridership by reallocating existing bus services. Such bus network re-designs may be an effective, low-cost option available to increase transit ridership. Additional analysis is needed to better understand the effect's true magnitude and evaluate local conditions, but the strategy appears promising. Empirical research suggests that past bus network redesigns increased ridership by about 5% after controlling overall service levels, population growth, and other factors. Provisioning exclusive lanes to bus service in congested or high-ridership corridors enhance the value of these transit services.

While our analysis focuses on ridership, it is crucial to recognize that the considerations in designing a transit service plan extend beyond total ridership. The spatial differences observed in Figure 5 through Figure 10 highlight that there will naturally be winners and losers in any system changes. The equity impacts of such changes are an essential consideration, as is the need to provide service to those who need it even if the total ridership on a route is modest. This coverage versus capacity balance has been the focus of past transit network re-designs. It highlights the need to define or update their existing service standards to reflect better transportation needs and the availability of different services. By setting these standards upfront and before network design, the agency is ready to balance the customer needs and have technical reasons for provisioning such service quantity and quality [2], [29].

Moreover, while our current study uses commercially available CityCast that can capture current travel behavior changes such as those seen with COVID-19, tools within the MATSim framework can generate local area activity-based transport demand through open data sources. For example, Census data, OpenStreetMaps, GTFS feeds, shapefiles describing land use and land cover, and transport data like traffic counts, travel surveys can be used. Therefore, MATSim based analysis and scenario generation are spatially transferable to any arbitrary region. MATSim in Berlin and Ruhr, Germany, are the best examples of such experimental transfer of procedures [33].

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: V. Goyal, G. Erhardt, J. Kressner, C. Brakewood, K. Watkins; data collection: V. Goyal, J. Kressner; analysis and interpretation of results: V. Goyal, G. Erhardt, J. Kressner, K. Watkins; draft manuscript preparation: V. Goyal, G. Erhardt, J. Kressner, S. Berrebi, C. Brakewood, K. Watkins. All authors reviewed the results and approved the final version of the manuscript.

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